

OPTIMIZATION METHOD OF THRUST JACK CONTROL FOR SHIELD TBM CONTINUOUS EXCAVATION

TECHNICAL FIELD

The present invention relates to an optimization method of thrust jack control for shield TBM continuous excavation, and more specifically, to a method for optimizing thrust jack control by using a sine function or a linear function to calculate optimally thrusts to be applied by thrust jack groups in operation when the thrust jack groups installed in a circumferential direction are sequentially retracted (turned off sequentially) in order to perform continuous excavation by a cutter head and spiral lining simultaneously, and to maintain a center of thrust (COT) of thrust jack groups in operation constant and the resultant thrust constant.

The present application claims priorities based on Korean Patent Application No. 10-2023-0124381 (title: Method of thrust jack control for shield TBM continuous excavation, filed on September 18, 2023) and Korean Patent Application No. 10-2023-0144263 (title: Optimization method of thrust jack control linear function for shield TBM continuous excavation, filed on October 26, 2023), the disclosures of which are incorporated herein in its entirety.

BACKGROUND ART

Usually, a TBM (Tunnel Boring Machine) is a tunnel excavator that excavates by crushing rock by rotating a cutter head equipped with multiple disc cutters, and can minimize noise and vibration, and all tunnel construction processes from tunnel excavation to segment assembly and discharge of excavated rock or soil can be mechanized and automated.

During the above processes, the segment assembly is for lining the tunnel wall, and is

performed by assembling segments made of precast concrete into a circle. Specifically, when the cutter head excavates a rock, the segments are assembled behind it to create a lining wall in a shape of a circular ring, and the cutter head excavates the rock again using the newly manufactured lining wall as a support. In this case, the excavation by the cutter head is stopped while assembling the segments to make the circular ring-shaped wall, and excavation is restarted after the assembly of this wall is completed. Therefore, there is a problem that excavation and lining wall assembly are alternately repeated, and thus the tunnel excavation speed decreases.

To solve this problem, as shown in Fig. 1, a method of assembling segments 3 to make a spiral lining was proposed. Specifically, a cutter head 2 excavates using the spiral lining as a reaction support, but thrust jacks 1 only in a part 4 where the segment 3 is to be installed are retracted (i.e., turned off), and in a remaining part, thrust jacks 1 are maintained in a state supported by the segment 3 so as to continuously provide a reaction force to the cutter head 2, so that rock excavation and segment installations can be performed simultaneously, and thus the tunnel excavation speed can be increased.

In this way, in order to newly install the segment 3, a plurality of thrust jacks 1 arranged along the circumferential direction are sequentially retracted, a position of the center of thrust (abbreviated as 'COT') by the remaining thrust jacks 1 except for the retracted thrust jacks 1, must be constant and a magnitude of the thrust (F_{area}) must be constant so that an excavation direction can be maintained constant.

However, there are problems that it is very difficult to maintain the position of the center of thrust constant and the sum of the thrust (F_{area}) constant with the remaining thrust jacks 1.

DISCLOSURE

Technical Goals

The present invention has been proposed to solve the above-described problems, and a purpose of the present invention is to provide a method for optimizing thrust jack control by using a sine function or a linear function to calculate optimally the thrusts to be applied by thrust jack groups in operation when the thrust jack groups installed in a circumferential direction are sequentially retracted (turned off sequentially) in order to perform continuous excavation by a cutter head and spiral lining simultaneously, and to maintain the center of thrust (COT) of thrust jack groups in operation constant and the resultant thrust constantly maximized.

Another purpose of the present invention is to provide a recording medium that records a computer program that implements the above-described control optimization method.

Technical Solution

In order to achieve the above-described purpose, a method for optimizing a control of thrust jacks for continuous excavation of a shield TBM according to a preferred embodiment of the present invention is a method for controlling thrusts applied by remaining thrust jack groups, except for a thrust jack group that is being retracted (operation being stopped) to install a new segment in order to continuously construct a spiral lining in a tunnel excavated by a cutter head.

Specifically, when the thrust jack groups are sequentially retracted to install the segment, the thrusts applied by the remaining thrust jack groups are optimally calculated by a condition that a center of the thrust (COT(x), COT(y)) is maintained constant, a condition that the resultant force ($F_{\text{area-consecutive}}$) of the thrusts applied by the remaining thrust jack groups is

maintained constant, and a condition that distributions of the thrusts follow a predetermined function.

The predetermined function may be a sine function. Considering that thrusts of the thrust jack groups adjacent to the retreated (turned off) thrust jack group should be greatly increased, the sine function may be desirable for optimization. In this case, coordinates of the center of thrust (COT(x), COT(y)), the thrust (F_i), and the resultant force ($F_{\text{area-consecutive}}$) can be calculated by the following equation.

$$\text{COT}(X) = \frac{\sum_{i=1}^n F_i X_i}{F_{\text{area-consecutive}}}$$

$$\text{COT}(Y) = \frac{\sum_{i=1}^n F_i Y_i}{F_{\text{area-consecutive}}}$$

$$F_i = F_0 + A \times \sin \frac{\pi \times (\theta_i - \theta_c)}{w}$$

$$F_{\text{area-consecutive}} = \sum_{i=1}^n F_i$$

in the above equation,

$i = 1 \sim n$

n : the number of thrust jack groups

F_0 : y-intercept at the starting point

F_i : thrust of i-th thrust jack group

θ_i : an angle expressed in radians based on the origin between a position (X_i, Y_i) of the thrust jack group and the +y-axis.

θ_c : the x-value of the starting point (θ_c, F_0)

$$w = \frac{\text{period in } x \text{ axis direction}}{2} \quad (w \text{ is limited to within } 1\pi)$$

$$A = \frac{\text{amplitude in } y \text{ axis direction}}{2}$$

Meanwhile, the above predetermined function may be a linear function. In this case, when the thrust jack groups are sequentially retracted (operation stopped), the coordinates of the center of thrust (COT(x), COT(y)), the thrust (F_i) of each thrust jack group, and the resultant force ($F_{\text{area-consecutive}}$) can be calculated by the following equation.

$$\text{COT}(X) = \frac{\sum_{i=1}^n F_i X_i}{F_{\text{area-consecutive}}}$$

$$\text{COT}(Y) = \frac{\sum_{i=1}^n F_i Y_i}{F_{\text{area-consecutive}}}$$

$$F_i = a_j(\theta_i - b_j) \quad , \quad (j = 1, 2)$$

$$F_{\text{area-consecutive}} = \sum_{i=1}^n F_i$$

in the above equation,

$i = 1 \sim n$

n : the number of thrust jack groups

a_j : the slope of the linear function

$$|a_2| = |a_1|$$

$-a_j b_j$: the y-intercept of the starting point

b_j : the x-intercept of the starting point

θ_i : an angle expressed in radians based on the origin between the position of the thrust

jack group and the +y-axis.

F_i is calculated by equation (4-1) or (4-2) below, and a thrust of the retracted thrust jack group is 0, and the calculation formula for F_i changes based on a point where graphs of equations (4-1) and (4-2) meet, and an area under the F_i graphs becomes $F_{\text{area-consecutive}}$.

$$F_i = a_1(\theta_i - b_1) \dots\dots\dots(4-1)$$

$$F_i = a_2(\theta_i - b_2) \dots\dots\dots(4-2)$$

When all thrust jack groups operate and provide the thrusts, the following equation can be satisfied. When all thrust jack groups operate, the thrust of the respective thrust jack group is calculated to maximize the resultant force ($F_{\text{area-conventional}}$), and when the thrust jack groups are sequentially stopped to install a new segment, the thrusts of the thrust jack groups can be calculated again so that the resultant force ($F_{\text{area-conventional}}$) is maintained.

$$F_{\text{area-conventional}} = \sum_{i=1}^n F_i$$

In the spiral lining, a central part of the newly installed segment corresponds to the connection part of the previously installed segments, and two thrust jack groups are installed to correspond to each segment to provide thrust.

The two thrust jack groups may be installed on both sides of the central part respectively.

The segment may include two circumferential side faces 14 formed in the circumferential direction of the tunnel, and two tunnel longitudinal side faces 15 formed in the longitudinal direction of the tunnel. In addition, the circumferential side face 14 may include a first side face 11, a second side face 12, and a step 13 connecting the first and second sides 11,

12. A tip of the thrust jack group may apply thrust to the first side 11 and the second side 12 respectively. At this time, the first side 11 and the second side 12 may be perpendicular to the tip of the thrust jack group.

The present invention includes a recording medium that contains a computer program for implementing the control optimization method and can be read by a computer. Specifically, when coordinates of the thrust jack groups and a center of thrust of the thrust jack groups are input, the computer program optimally calculate the thrust to be applied by each thrust jack group using a sine function or a linear function in the case where all the thrust jack groups are in operation and in the case where a predetermined thrust jack group is sequentially retracted.

Advantageous Effects

The present invention has following effects.

First, the present invention can calculate thrusts optimally to be applied by thrust jack groups in operation when thrust jack groups installed in a circumferential direction are sequentially retracted (stopped the thrust sequentially) in order to perform continuous excavation by a cutter head and spiral lining simultaneously, and to maintain the center of thrust (COT) of the thrust jack groups in operation constant and the total thrust constantly maximized.

Second, a recording medium recording a computer program capable of performing the above-mentioned optimization calculation is provided.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a perspective view showing a spiral lining formed using segments during continuous excavation by a shield TBM.

Fig. 2 is a perspective view showing a spiral lining formed by arranging segments in a

spiral shape according to one embodiment of the present invention, showing that one rotation is formed by 7.5 segments. Fig. 2 is a view looking from the front (cutter head) side to the rear (segment) side.

Fig. 3 is a drawing showing a spiral lining made of segments of Fig. 2 and an arrangement of the thrust jack groups corresponding to the spiral lining.

Fig. 4 is a drawing showing an exemplary location of a center of thrust (COT).

Fig. 5 is a drawing showing numbers of the thrust jack groups (G1 ~ G15) and numbers of the thrust jack groups that are retracted in each case (#1 ~ #16). Fig. 5 is a drawing looking from the rear toward the front (cutter head).

Fig. 6 is a drawing showing an exemplary location of the center of thrust (COT).

Figs. 7a ~ 7b are drawings showing thrusts that each thrust jack group should apply when all thrust jack groups are in operation (case #1) and thrusts that remaining thrust jack groups should apply when a predetermined thrust jack group is sequentially retracted (operation stopped) (case #2 ~ #8) when a sine function is applied to the control optimization.

Figs. 8a ~ 8b are drawing showing thrusts that remaining thrust jack groups should apply when a predetermined thrust jack group is sequentially retracted (operation stopped) (case #9 ~ #16) when a sine function is applied to the control optimization.

Fig. 9 is a drawing showing thrust (F) to be applied by each thrust jack group when all thrust jack groups are in operation (case #1) and a thrust (F) to be applied by remaining thrust jack groups when a predetermined thrust jack group is sequentially retracted (operation stopped) (cases #2 ~ #16) when a linear function is applied to the control optimization.

Fig. 10 is a drawing showing thrust (F) to be applied by each thrust jack group in cases #1 ~ #16 of FIG. 9, respectively.

Fig. 11 is a perspective view showing a step type segment.

Fig. 12 is a drawing showing a spiral lining made of the step type segments of Fig. 11 and an arrangement of the thrust jack groups corresponding to the spiral lining.

DETAILED DESCRIPTION

Hereinafter, the present invention will be described in detail with reference to the attached drawings. In this specification, 'horizontal' means not only horizontal in a mathematical sense, but also an inclined state close to horizontal. And, 'vertical' means not only vertical in a mathematical sense, but also an inclined state close to vertical.

And, a thrust jack group means a thrust jack group composed of one or more thrust jacks, and the thrust jacks forming the thrust jack group extend or contract (retract) simultaneously. The drawing attached herewith shows that the thrust jack group is composed of two thrust jacks, but a number of thrust jacks forming the thrust jack group may be increased or decreased as needed.

[First embodiment: Using sine functions for control optimization]

Fig. 2 is a perspective view showing a spiral lining in which segments are arranged in a spiral shape according to one embodiment of the present invention, and Fig. 3 is a drawing showing the spiral lining composed of the segments and an arrangement of a thrust jack group corresponding to the spiral lining. In Fig. 2, one rotation is formed by 7.5 segments. Fig. 2 is a view looking from a front (cutter head) side to a rear (segment) side.

The spiral lining is made by arranging segments 3 in a spiral shape. In the drawing, 7.5 segments 3 of the same size are arranged for one spiral rotation, and half of the first segment 3 and half of the eighth segment 3 are arranged so that they overlap. Therefore, the segments 3 are arranged in a same manner every 4π (720°). In addition, the thrust that each thrust jack

group must apply may be repeated every 4π (720°) if a tunnel is straight or a curvature of the tunnel is constant.

Meanwhile, the number of segments 3 for one spiral rotation can be increased or decreased as needed, but in this specification, for a convenience of explanation, an example of 7.5 segments 3 of the same size being arranged to form one spiral rotation will be explained.

The segment 3 is a precast concrete product for lining a portion excavated by the cutter head 2 when excavating a tunnel with a TBM, and a number of reinforcing bars or wire meshes can be embedded therein. This segment is well known to those skilled in this art, so a detailed description thereof will be omitted here.

In addition, in this specification, two thrust jack groups correspond to one segment 3, and one thrust jack group is composed of two thrust jacks 1, and each group is arranged to correspond to each side of a center of a circumferential direction of the segment 3. In addition, the thrust jack group on each side can be operated independently.

Fig. 4 shows 15 groups (i.e., 30 thrust jacks) arranged along the circumferential direction. The numbers 1 ~ 30 represent the thrust jack numbers, and (COT (X), COT (Y)) represent coordinates of the center of thrust (COT).

In addition, in Fig. 5, G1 ~ G15 represent numbers of the thrust jack groups, ① ~ ③⑩ represent numbers of the thrust jacks, and #2 ~ #16 represent case numbers, and the thrust jack groups corresponding to the corresponding cases are retracted (turned off). For example, in case #2, the thrust jack groups G7 and G8 are retracted (stopped) and the remaining thrust jack groups operate normally, and in case #6, the thrust jack groups G15 and G1 are retracted and the remaining thrust jack groups operate normally.

In this specification, in order to explain the present invention, the case in which all

thrust jack groups operate is represented as case #1 (Conventional), and the case in which a specific thrust jack group is stopped (retracted) is represented as case #2 ~ #16 (Consecutive).

In order to calculate an optimal thrust to be applied by the thrust jack group by numerical analysis, an optimization function of a known numerical analysis computer program can be applied and used. In case #1, the function called **fmincon** of the computer program can be used, and in cases #2 ~ #16, the function called **fsolve** of the computer program can be used. As is known to those skilled in this art, **fmincon** is a function used to find a minimum of a nonlinear multivariable function with constraints. **fmincon** is a gradient-based method designed to work on problems where both an objective function and a constraint function are continuous and have continuous first-order derivatives. And **fsolve** is a function used to solve nonlinear simultaneous equations. This is summarized in Table 1 below.

[Table 1]

No.	Case	function	purpose
1	all thrust jack groups operate (case #1)	fmincon (constrained nonlinear optimization)	Calculating coefficients of a sine function that satisfies conditions that a position of COT is constant and that $F_{\text{sum}}(F_{\text{area}})$ is maximum.
2	A predetermined thrust jack group is retracted (stop operation) (case #2 ~ #16)	fsolve (Nonlinear equation solving)	Calculating a thrust distribution of the thrust jacks and coefficients of sine function that satisfy conditions that the $F_{\text{sum}}(F_{\text{area}})$ and COT of case #1 are constantly maintained.

And, configurations of the above functions (**fmincon**, **fsolve**) are explained as Table 2 below.

[Table 2]

	Mathematical formula for sine function
Number of constant = 47	Coordinates of thrust jack groups (X_i, Y_i, θ_i) : 45 Coordinate of center of thrust (COT(X), COT(Y)) : 2
variables	number of variables : 19 F_i : thrust of thrust jack group (15 variables) $0 < F_i \leq 100$: in case of conventional (when all thrust jack groups operate) $F_i = F_0 + A \times \sin \frac{\pi \times (\theta_i - \theta_c)}{w}$ (4 variables : F_0, A, θ_c, w) in the above equation, $i = 1 \sim n$ n : number of thrust jack groups (Number of thrust jack groups is 15 in table 3 and Fig. 7a~8b) F_0 : y-intercept of the starting point θ_c : x-value of the starting point (θ_c, F_0) $w = \frac{\text{period in x axis direction}}{2}$, (limited to within 1π)(A) $A = \frac{\text{amplitude in y axis direction}}{2}$
Objective function (in the case of conventional)	$F_{\text{area-conventional}} = \sum_{i=1}^n F_i$ Condition for the conventional = F_{area}(sum of the thrusts) is maximum. Condition for the consecutive (Condition for continuous excavation) = maintaining the F_{area} (F_{area} is the maximum thrust in case of the conventional). [When conventional (i.e., when all thrust jack groups operate), calculate force (thrust) distributions of 15 thrust jack groups that maximize the force sum ($F_{\text{area-conventional}}$), and then find force distributions again to maintain the force sum (resultant force, $F_{\text{area-conventional}}$) of these 15 thrusts under the condition for the consecutive (when the thrust jack groups are sequentially stopped for continuous excavation).]
Nonlinear constraints	$\text{COT}(X) = \frac{\sum_{i=1}^n F_i X_i}{F_{\text{area-conventional}}}, \quad \text{COT}(Y) = \frac{\sum_{i=1}^n F_i Y_i}{F_{\text{area-conventional}}}$ $F_i = F_0 + A \times \sin \frac{\pi \times (\theta_i - \theta_c)}{w}, \quad i = 1 \sim n$ $F_{\text{area-conventional}} = \sum_{i=1}^n F_i$ Condition for continuous excavation. That is to say, thrust jack groups are sequentially retracted to install a segment.

In equation (A) of the table above, ‘limited to within 1π ’ is a condition that induces a period of the sine function to be formed within $1/2$ period (π), as shown in Figs. 7a and 8a. If it exceeds $1/2$ period, the function becomes an increase-decrease-increase and becomes a cubic function, and if it exceeds 1 period, it becomes a quaternary function having an increase-decrease-increase-decrease, which becomes too complicated in practice. Therefore, the function is derived so that it becomes a convex function on only one side like a quadratic function, so that visibility and practicality are maintained at the same time.

Among the 47 constants, the coordinates (X_i , Y_i , θ_i) of the 15 thrust jack groups are constants already determined by a mechanical structure of a TBM ($15 \times 3 = 45$), and the coordinates of the center of thrust (COT(X), COT(Y)) are two constants (coordinates of the x and y axes) that a user inputs into a computer program. θ_i is an angle that the position (X_i , Y_i) of the thrust jack group makes with the +y axis (see Fig. 5) centered on the origin, expressed in radians.

In this embodiment, optimization means a combination of thrust jack groups in which the coordinates of the center of thrust are maintained constant and the thrust is maximized (the resultant force of the thrust jack groups is maximized. In other words, the resultant force $F_{\text{area-conventional}}$ (F_{sum}) of case #1 is maintained) in all cases of continuous excavation (#2 ~ #16). At this time, the thrusts of the thrust jack groups should have a distribution of a sine function. Considering that the thrusts of the thrust jack groups adjacent to the thrust jack group that is stopped should be greatly increased, this sine function is desirable for optimization.

Below, TBM continuous excavation specifications (7.5 segments) with a diameter of 7910 mm will be explained as an example. According to a specification table of the TBM, the thrust of one thrust jack group has a maximum of 400 tons (i.e., two 200-ton thrust jacks form one group). In this calculation, the maximum thrust was set to 100 tons (25% of the maximum

thrust) for case #1.

Fig. 6 shows 25 COTs (circle dots and rectangular dot) for the cutter head (having an outer diameter 7910 mm) of the TBM as an example. By using the thrust jack control method according to the present invention, when excavating a tunnel with a straight track and a curved track, it is possible to obtain an optimization DATA (an optimal value of the thrust that each thrust jack group should apply) for each of these COTs. However, in order to avoid duplication of explanation, only the case where the coordinates of the COT are $X=0$, $Y=-400$ (the rectangular dot in Fig. 6) will be described below.

Table 3 below shows results calculated by applying the functions and conditions in Tables 1 and 2, and Figs. 7a and 7b show thrusts that each thrust jack group should apply when all thrust jack groups are in operation (case #1) and the thrust that the remaining thrust jack groups should apply when a predetermined thrust jack group retreats (stops operation) (cases #2 to #8).

And, Figs. 8a and 8b show thrusts that the remaining thrust jack groups should apply when a predetermined thrust jack group retreats (cases #9 to #16).

[Table 3]

Jack Cyl	x (mm)	y (mm)	Case No.	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16
			No. of Turned OFF	Conventional	7.8	9.10	11.12	13.14	15.1	2.3	4.5	6.7	8.9	10.11	12.13	14.15	1.2	3.4	5.6
#1	1134	3490	F1	63	44	17	36	80	0	142	118	70	25	22	57	103	0	134	96
#2	2456	2727	F2	72	71	42	49	79	111	0	127	93	53	42	62	98	0	136	113
#3	3353	1493	F3	80	96	67	62	80	105	0	133	113	80	61	68	94	123	0	126
#4	3670	0	F4	87	118	90	75	81	100	126	0	130	103	80	76	90	115	0	136
#5	3353	-1493	F5	93	135	110	89	84	96	119	0	142	124	97	84	89	108	130	0
#6	2456	-2727	F6	97	147	126	101	88	93	112	135	0	139	113	92	88	101	124	0
#7	1134	-3490	F7	100	0	139	112	92	91	105	129	0	149	125	101	89	95	117	141
#8	-384	-3650	F8	100	0	146	121	98	90	98	121	147	0	134	108	91	90	109	135
#9	-1835	-3178	F9	99	149	0	128	104	90	91	111	138	0	140	115	94	87	100	125
#10	-2969	-2157	F10	95	138	0	132	110	91	85	99	125	145	0	121	99	86	90	111
#11	-3590	-763	F11	90	121	138	0	115	93	81	86	107	132	0	125	104	86	81	95
#12	-3590	763	F12	84	100	126	0	121	97	78	72	86	115	131	0	110	87	72	76
#13	-2969	2157	F13	76	76	109	128	0	101	76	57	63	92	121	0	116	91	64	57
#14	-1835	3178	F14	68	49	88	121	0	106	75	44	38	67	107	129	0	95	57	37
#15	-384	3650	F15	59	20	66	112	133	0	77	31	12	40	91	127	0	101	52	17
Force SUM			Fsum	1265	1265	1265	1265	1265	1265	1265	1265	1265	1265	1265	1265	1265	1265	1265	1265
Force Max			Fmax	100	149	146	132	133	111	142	135	147	149	140	129	116	123	136	141
Force Ratio			Fratio	1.00	1.49	1.46	1.32	1.33	1.11	1.42	1.35	1.47	1.49	1.40	1.29	1.16	1.23	1.36	1.41
COT			coT(X)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			coT(Y)	-400	-400	-400	-400	-400	-400	-400	-400	-400	-400	-400	-400	-400	-400	-400	-400
Mx, My			MxSum	-506	-506	-506	-506	-506	-506	-506	-506	-506	-506	-506	-506	-506	-506	-506	-506
			MySum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F = Fo + Asin[$\pi(\theta_i - \theta_c)/w$]			Fo	56.7	17.8	29.3	68.8	107.6	116.8	110.5	69.3	28.9	18.0	47.7	89.6	119.0	123.3	91.1	47.5
			A	43.4	136.9	119.6	64.4	28.4	-27.2	35.2	68.2	121.7	136.2	93.2	39.8	31.0	37.9	44.9	96.3
			θ_c	-0.10	-0.18	0.41	1.26	3.84	0.18	-3.89	-1.40	-0.48	0.11	0.76	2.17	-7.17	-5.25	-2.34	-0.86
			w	6.28	6.28	6.28	6.28	6.28	6.28	6.28	6.28	6.28	6.28	6.28	6.28	6.28	6.28	6.28	6.28

As shown in the table above, the values of F_0 , θ_c , w , and A are calculated for each of

cases #1 ~ #16, and the optimal values of the thrusts that each thrust jack groups should apply are calculated using these values. Specifically, $F_1 \sim F_{15}$ represent optimal thrust values that each thrust jack group should apply in cases #1 ~ #16. In addition, F_{SUM} ($=F_{area-consecutive}$) in Table 3 is a sum of the thrusts of all operating thrust jack groups, which is constant at 1265 tons in all cases. In addition, $COT(X)=0$, $COT(Y)=-400$, which are constant. Accordingly, a sum of the moments by each thrust jack group is constant as $M_{xSum}=-506$, $M_{ySum}=0$.

In addition, a maximum value (F_{max}) among thrusts of the thrust jack groups are 149 tons, and a ratio of F_{max} and $F_{conventionalmax}$ ($F_{ratio} = F_{max} / F_{conventionalmax}$) is 1.49. The $F_{conventionalmax}$ is the maximum thrust (100 tons) of the thrust jack groups in Case #1.

When optimized with a sine function, $F_{SUM}(F_{area-consecutive})$ is greater than $F_{SUM}(F_{area-consecutive})$ when optimized with a linear function or a normal distribution function, which means that an efficiency when optimized with a sine function is greater than an efficiency when optimized with a linear function or a normal distribution function.

[Second embodiment : Using linear functions for control optimization]

When using linear functions for control optimization, just like the first embodiment, the function called `fmincon` can be used for the case #1, and the function called `fsolve` can be used for the cases #2 ~ #16. This is summarized in Table 4 below.

[Table 4]

No.	Case	function	purpose
1	all thrust jack groups operate (case #1)	fmincon (constrained nonlinear optimization)	Calculating coefficients of a linear function that satisfies conditions that a position of COT is constant and that $F_{sum}(F_{area})$ is maximum.

2	A predetermined thrust jack group is retracted (stop operation) (case #2 ~ #16)	fsolve (Nonlinear equation solving)	Calculating the thrust distribution of the thrust jacks and coefficients of linear function that satisfy conditions that the $F_{sum}(F_{area})$ and COT of case #1 are constantly maintained.
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And, configurations of the above functions (fmincon, fsolve) is explained as in Table 5 below.

[Table 5]

	Mathematical formula for a linear function
Number of constant = 47	Coordinates of thrust jack groups (X_i, Y_i, θ_i) : 45 Coordinate of center of thrust (COT(X), COT(Y)) : 2
variables	number of variables : 18 F_i : thrust of thrust jack group (15 variables) $0 < F_i \leq 200$: a maximum thrust of thrust jack is equal or less than 200 ton. $F_i = a_j(\theta_i - b_j)$, ($j = 1, 2$) (Since $-a_1 = a_2$, there are three variables: a_1, b_1, and b_2.) in the above equation, $i = 1 \sim n$ n : number of thrust jack groups (Number of thrust jack groups is 15 in table 6 and Fig. 9~10) a_j : Slope of a linear function $a_2 = a_1$ (The absolute values of the slopes of two linear functions are the same) $-a_j \cdot b_j$: y-intercept of the starting point, b_j : x-intercept of the starting point
Objective function (resultant thrust of conventional TBM = resultant thrust of continuous excavation TBM)	$F_{\text{area}} = \sum_{i=1}^n F_i$ The resultant thrust ($F_{\text{area-conventional}}$) when a TBM excavates using the conventional method (i.e., when all thrust jack groups are operating) = the resultant thrust ($F_{\text{area-consecutive}}$) when a TBM excavates using the continuous excavation method. In other words, when a TBM excavates using the conventional method (i.e., when all thrust jack groups are operating), the force (thrust) distributions of $n(15)$ thrust jack groups that maximize a resultant thrust ($F_{\text{area-conventional}}$) are calculated, and a force (thrust) distribution is calculated again so that the resultant thrust of these $n(15)$ is maintained under the continuous excavation condition (when the thrust jack groups are sequentially stopped for the continuous excavation).
Constraints	$\text{COT}(X) = \frac{\sum_{i=1}^n F_i X_i}{F_{\text{area-consecutive}}} \quad , \quad \text{COT}(Y) = \frac{\sum_{i=1}^n F_i Y_i}{F_{\text{area-consecutive}}}$ $F_i = a_j(\theta_i - b_j)$, ($j = 1, 2$) $F_{\text{area-consecutive}} = \sum_{i=1}^n F_i$ Conditions for a continuous excavation. That is to say, thrust jack groups are sequentially retracted to install a segment.

Among the 47 constants, the coordinates (X_i, Y_i, θ_i) of the 15 thrust jack groups are

constants already determined by a mechanical structure of the TBM ($15 \times 3 = 45$), and coordinates of the center of thrust (COT(X), COT(Y)) are two constants (coordinates of the x and y axes) that a user inputs into a computer program. The X_i and Y_i are coordinates that indicate the position of the i-th thrust jack group on the x and y axes, and the θ_i is an angle that the position of the i-th thrust jack group makes with the +y axis (see Fig. 5) centered on the origin, expressed in radians.

In this embodiment, optimization means a combination of thrust jack groups in which the coordinates of the center of thrust are maintained identically to the center of thrust of case #1 in all cases (#2 ~ #16) of continuous excavation and the resultant thrust is maximized (the resultant thrust of the thrust jack groups is maximized. In other words, the resultant force $F_{\text{area-conventional}}$ (F_{sum}) of case #1 is maintained in cases #2 ~ #16). At this time, the thrusts of the thrust jack groups have a distribution of a linear function and satisfy the condition of $-a_1 = a_2$.

Considering that the thrusts of the thrust jack groups adjacent to the thrust jack group that is stopped should be greatly increased, the linear function is considered desirable for optimization.

Below, a description will be based on a TBM continuous excavation specifications (7.5 segments) with a diameter of 7910 mm. According to a manufacturer's specifications, thrust of one thrust jack group has a maximum of 400 tons (i.e., two 200-ton thrust jacks form one group). In this calculation, the thrust of one group was set to 200 tons (50% of the maximum thrust) as the maximum when the TBM excavates using the conventional method (conventional TBM, i.e., case #1).

Using the thrust jack control method according to the present invention, when excavating a tunnel having a straight track and a curved track, it is possible to have an optimal DATA (an optimal thrust value that each thrust jack group should apply) for COT. However, in

order to avoid duplication of explanation, the following description will only explain the case where the coordinates of COT are X=0, Y=-400.

Table 6 shows results calculated by applying the functions and conditions of Tables 4 and 5, more specifically by applying conditions of $F_{\text{area}}=1265$ tons, $\text{COT}=(0, -400)$, $-a_1=a_2$, and Fig. 9 shows thrusts that each thrust jack group should apply in Case #1, and thrusts that each thrust jack group should apply in Cases #2 ~ #16 in the Table 6, respectively. In Fig. 9, the x-axis represents the number of the thrust jack group, and the y-axis represents the thrust (ton) of each thrust jack group.

And Fig. 10 shows thrusts that each thrust jack group should apply in Cases #1 ~ #16 of Table 6, respectively. In Fig. 10, a distance from the origin represents a magnitude of the thrust, and the numbers (1 ~ 15) on the circumference of the outer circle represent the numbers of the thrust jack groups.

In Table 6 and Figs. 9 ~ 10, the thrust of the retracted thrust jack group is set to 0, and the calculation formula for F_i is changed based on the point where Equations (1) and (2) meet, and the thrust of each thrust jack group forms a straight line on both sides of the point, and area under the graph of F_i becomes $F_{\text{area-conventional}}$ (the maximum value of F_{sum} in Case #1), so that it can be calculated by either Equation (1) or (2) below.

$$F_i = a_1(\theta_i - b_1) \quad \dots\dots\dots(1)$$

$$F_i = a_2(\theta_i - b_2) \quad \dots\dots\dots(2)$$

[Table 6]

Jack Cyl.	X (mm)	Y (mm)	Case No. No. of tu rned off	#1 Conven- tional	#2 G7,G8	#3 G9,G10	#4 G11,G12	#5 G13,G14	#6 G15,G1	#7 G2,G3	#8 G4,G5	#9 G6,G7	#10 G8,G9	#11 G10,G11	#12 G12,G13	#13 G14,G15	#14 G1,G2	#15 G3,G4	#16 G5,G6
G1	1134	3490	F1	66	48	29	43	86	0	141	110	69	34	33	55	104	0	131	90
G2	2456	2727	F2	72	70	48	54	82	109	0	122	88	55	48	63	99	0	139	106
G3	3353	1493	F3	78	91	66	65	77	105	0	134	107	76	63	70	95	118	0	121
G4	3670	0	F4	84	112	85	76	72	101	123	0	126	97	78	77	91	113	0	137
G5	3353	-1493	F5	90	133	103	86	85	98	117	0	145	118	92	85	87	108	132	0
G6	2456	-2727	F6	96	154	122	97	90	94	112	143	0	139	107	92	83	103	124	0
G7	1134	-3490	F7	103	0	140	108	95	91	106	131	0	160	122	99	88	98	115	152
G8	-384	-3650	F8	106	0	159	119	100	87	100	119	158	0	137	107	93	93	107	137
G9	-1835	-3178	F9	99	157	0	130	104	88	94	108	139	0	151	114	97	88	99	121
G10	-2969	-2157	F10	93	136	0	141	109	91	88	96	120	150	0	121	101	78	90	106
G11	-3590	-763	F11	87	115	140	0	114	95	82	84	101	129	0	129	105	83	82	90
G12	-3590	763	F12	81	94	121	0	118	98	67	72	82	108	131	0	109	88	74	74
G13	-2969	2157	F13	75	73	103	126	0	102	73	60	63	87	116	0	113	93	65	59
G14	-1835	3178	F14	69	51	84	115	0	105	79	49	44	66	101	130	0	98	57	43
G15	-384	3650	F15	63	30	66	105	133	0	84	37	24	45	86	123	0	103	49	28
FORCE	Sum		Fsum	1265	1265	1265	1265	1265	1265	1265	1265	1265	1265	1265	1265	1265	1265	1265	1265
	Min		Fmin	63	30	29	43	72	87	67	37	24	34	33	55	83	78	49	28
	Max		Fmax	106	157	159	141	133	109	141	143	158	160	151	130	113	118	139	152
	Max - Min		Fdiff	42	127	129	97	60	21	74	106	134	126	118	75	30	40	90	125
	Max / Min		Fratio	1.67	5.20	5.45	3.26	1.83	1.24	2.11	3.88	6.46	4.72	4.53	2.35	1.36	1.51	2.85	5.49
COT			COT(X)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			COT(Y)	-400	-400	-400	-400	-400	-400	-400	-400	-400	-400	-400	-400	-400	-400	-400	-400
			MxSum	-506	-506	-506	-506	-506	-506	-506	-506	-506	-506	-506	-506	-506	-506	-506	-506
			MySum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mx, My			a1	14.46	50.62	44.14	25.84	-11.28	-8.40	-14.01	28.15	45.56	50.10	35.19	17.50	-9.73	11.91	19.88	37.20
			b1	-4.4	-0.7	-0.4	-1.5	7.9	13.5	10.3	-3.7	-1.3	-0.5	-0.7	-3.0	10.9	11.0	-6.4	-2.2
			a2	-14.46	-50.62	-44.14	-25.84	11.28	8.40	14.01	-28.15	-45.56	-50.10	-35.19	-17.50	9.73	11.91	-19.88	-37.20
			b2	10.44	6.67	7.57	10.12	-5.68	-6.89	0.05	7.38	6.61	6.98	8.53	13.08	-6.37	-2.57	8.53	6.82

$$y1 = a1(\theta i - b1)$$

$$y2 = -a1(\theta i - b2)$$

As shown in Table 6, a_1 , a_2 , b_1 , and b_2 are calculated for each of Cases #1 ~ #16, and an optimal value of the thrust (F_i) that each thrust jack group should apply is calculated using these calculated values. Specifically, $F_1 \sim F_{15}$ represent the optimal values of the thrust that each thrust jack group should apply in Cases #1 ~ #16.

In Table 6, F_{SUM} ($F_{area-conventional}=F_{area-consecutive}$) is sum of all thrusts of the operating thrust jack groups, which is constant at 1265 ton in all cases. In addition, $COT(X)=0$, $COT(Y)=-400$, which is constant in all cases. Accordingly, sum of moments by each thrust jack group is constant as $M_{xSum}=-506$, $M_{ySum}=0$. For reference, M_{xSum} is a moment generated around the x-axis by $F_{SUM}(F_{area-consecutive})$, and M_{ySum} is a moment generated around the y-axis by $F_{SUM}(F_{area-consecutive})$.

According to the research of the present inventor, under a condition that a thrust sum value (F_{sum}) is the same, when optimized with a sine function, the maximum/minimum ratio (F_{ratio}) can be maintained smaller. However, since the sine function has 4 variables, it is difficult for workers at a tunnel site to understand intuitively and impossible to optimize at the site. Accordingly, there is a disadvantage in that the optimization results must be provided in advance in order to be used.

In contrast, when optimized with a linear function, the maximum/minimum ratio (F_{ratio}) increases, but the number of optimization operating variables can be reduced by one to be three, and a fitting is possible by the three variables. Since the linear function is simple and intuitive, workers at a construction site can easily derive the optimization solution graphically.

Under normal conditions, an efficiency of the sine function is high, but under conditions such as maximum thrust/minimum turning radius excavation, it is judged that a tunnel site work speed will be higher when using the linear function.

[modified embodiments of segments]

The segment is not limited to the structure illustrated in Figs. 2 and 3, and can be modified in various ways within a scope that can implement the technical idea of the present invention. For example, Fig. 11 is a perspective view showing a step type segment, and Fig. 12 is a drawing showing a spiral lining made of the step type segments and an arrangement of a thrust jack group corresponding to the spiral lining.

The step type segment 3a includes a body, four side faces 14, 15 of the body, an inner face 16 facing an inside of a tunnel, and an outer face facing an outside of the tunnel.

Among the four side faces 14, 15, two side faces 14 in the tunnel circumferential direction may be parallel to each other, and two side faces 15 in the tunnel progression direction (tunnel length direction) may be formed at an inclined angle to each other. In addition, the inner face 16 and the outer face may be spaced apart at equal intervals so that the thickness is the same throughout the segment.

The two circumferential side faces 14 may include a first side face 11, a second side face 12, and a step 13 respectively. The first side face 11 and the tunnel longitudinal side face 15 are perpendicular to each other, and the second side face 12 and the tunnel longitudinal side face 15 are perpendicular to each other. By these structures, when a tip of the thrust jack 1 contacts the first and second side faces 11, 12 and applies thrusts, the thrust jack 1 and the first and second side faces 11, 12 are perpendicular, so that buckling or bending of the thrust jack 1 can be prevented.

The step 13 is formed in a center of the circumferential side face 14, and the step 13 is formed to be perpendicular to the first and second side faces 11, 12 or inclined at a predetermined angle. As described above, two thrust jack groups can be arranged in one segment 3a, and one of the thrust jack groups can be arranged on one side of the step 13, and

the other thrust jack group can be arranged on the other side of the step 13.

WHAT IS CLAIMED IS:

1. A method for optimizing a control of thrust jacks for continuous excavation of a shield TBM, characterized in that,

the method optimizes a control of thrusts applied by remaining thrust jack groups, except thrust jack groups that are retreated to install a segment in order to continuously construct a spiral lining and excavation by a cutter head simultaneously,

wherein when the thrust jack groups are sequentially retracted to install the segment, the thrusts applied by the remaining thrust jack groups are optimally calculated by a condition that a center of the thrust ($COT(x)$, $COT(y)$) is maintained constant, a condition that a resultant force ($F_{area-consecutive}$) of the thrusts applied by the remaining thrust jack groups is maintained constant, and a condition that a distribution of the thrust follows a predetermined function.

2. The method according to claim 1,

wherein the predetermined function is a sine function, and when the thrust jack groups are sequentially retracted, coordinates of the center of thrust ($COT(x)$, $COT(y)$), a thrust (F_i) of each thrust jack group, and the resultant force ($F_{area-consecutive}$) are calculated by following equations.

$$\text{COT}(X) = \frac{\sum_{i=1}^n F_i X_i}{F_{\text{area-consecutive}}}$$

$$\text{COT}(Y) = \frac{\sum_{i=1}^n F_i Y_i}{F_{\text{area-consecutive}}}$$

$$F_i = F_0 + A \times \sin \frac{\pi \times (\theta_i - \theta_c)}{w}$$

$$F_{\text{area-consecutive}} = \sum_{i=1}^n F_i$$

in the above equation,

$i = 1 \sim n$

n : number of the thrust jack groups

F_0 : y-intercept at a starting point

F_i : thrust of i -th thrust jack group

θ_i : an angle expressed in radians based on a origin between a position (X_i, Y_i) of the thrust jack group and a +y-axis.

θ_c : the x-value of the starting point (θ_c, F_0)

$$w = \frac{\text{period in } x \text{ axis direction}}{2}$$

$$A = \frac{\text{amplitude in } y \text{ axis direction}}{2}$$

3. The method according to claim 1,

wherein the predetermined function is a linear function, and when the thrust jack groups are sequentially retracted, coordinates of the center of thrust (COT(x), COT(y)), a thrust (F_i) of each thrust jack group, and the resultant force ($F_{\text{area-consecutive}}$) are calculated by following

equations.

$$\text{COT}(X) = \frac{\sum_{i=1}^n F_i X_i}{F_{\text{area-consecutive}}}$$

$$\text{COT}(Y) = \frac{\sum_{i=1}^n F_i Y_i}{F_{\text{area-consecutive}}}$$

$$F_i = a_j(\theta_i - b_j) \quad , \quad (j = 1, 2)$$

$$F_{\text{area-consecutive}} = \sum_{i=1}^n F_i$$

in the above equation,

$i = 1 \sim n$

n : number of the thrust jack groups

a_j : slope of the linear function

$$|a_2| = |a_1|$$

$-a_j b_j$: y-intercept of a starting point

b_j : x-intercept of a starting point

θ_i : angle expressed in radians based on a origin between a position of the thrust jack group and a +y-axis.

4. The method according to claim 3,

wherein F_i is calculated by equation (4-1) or (4-2) below, and a thrust of the retracted thrust jack group is 0, and a calculation formula for F_i changes at a point where graphs of equations (4-1) and (4-2) meet, and an area under a graph of F_i becomes $F_{\text{area-consecutive}}$.

$$F_i = a_1(\theta_i - b_1) \dots\dots\dots(4-1)$$

$$F_i = a_2(\theta_i - b_2) \dots\dots\dots(4-2)$$

5. The method according to claim 2 or 3,

wherein when all thrust jack groups operate and provide the thrusts, the following equation is satisfied,

wherein when all thrust jack groups operate, the thrust of each thrust jack group is calculated to maximize the resultant force ($F_{\text{area-conventional}}$), and when the thrust jack groups are sequentially stopped to install the segment, the thrusts of the thrust jack groups are calculated again so that the resultant force ($F_{\text{area-conventional}}$) is maintained.

$$F_{\text{area-conventional}} = \sum_{i=1}^n F_i$$

6. The method according to claim 5,

wherein a central part of the segment corresponds to the connection part of the previously installed segments, and two thrust jack groups are installed to correspond to each segment to provide the thrust, and the thrust jack group is installed on both sides of the central part respectively.

7. The method according to claim 6,

wherein the segment includes two circumferential side faces 14 formed in a circumferential direction of the tunnel, and two tunnel longitudinal side faces 15 formed in a longitudinal direction of the tunnel,

wherein the circumferential side face 14 includes a first side face 11, a second side face 12, and a step 13 connecting the first and second side faces 11, 12,

wherein a tip of the thrust jack group applies the thrust to the first side face 11 and the second side face 12 respectively, and the first side face 11 and the second side face 12 is perpendicular to the tip of the thrust jack group.

8. A recording medium that contains a computer program for implementing the method of the optimization control of claim 5 and can be read by a computer,

wherein when coordinates of the thrust jack groups and the center of thrust of the thrust jack groups are input, the computer program optimally calculate the thrust to be applied by each thrust jack group using a sine function or a linear function in the case where all the thrust jack groups are in operation and in the case where a predetermined thrust jack group is sequentially retracted.